Bacterial Relay for Energy Efficient Molecular Communications

Song Qiu[1], Werner Haselmayr[2], Bin Li[3], Chenglin Zhao[3], Weisi Guo[1]*

***Abstract*—In multi-cellular organisms, molecular signaling spans multiple distance scales and is essential to tissue structure and functionality. Molecular communications is increasingly researched and developed as a key subsystem in the Internet-of-Nano-Things (IoNT) paradigm. Whilst short range microscopic diffusion communications is well understood, longer range channels can be inefficient and unreliable. Static and mobile relays have been proposed in both conventional wireless systems and molecular communication contexts. In this paper, our main contribution is to analyze the information delivery energy efficiency of bacteria mobile relays. We discover that these mobile relays offers superior energy efficiency compared to pure diffusion information transfer over long diffusion distances. This research has widespread implications ranging from understanding biological processes to designing new efficient synthetic biology communication systems.**

I. Introduction

Molecular communications via diffusion (MCvD) utilizes chemical molecules as an alternative carrier for communication purposes [1], [2]. A key application area of MCvD is networking between nanomachines [3] for precision sensing and actuation tasks in nano-medicine [4]. Compared to electromagnetic communication systems, MCvD has numerous advantages in: energy efficient propagation [5] and information storage capacity [6], reliable propagation in challenging environments [7], [8], and bio-compatibility. However, its performance has important drawbacks such as low capacity, high latency, and sensitivity to environmental parameters [9]. For example, the *in vivo* diffusion environment can change relatively quickly due to the movement of cells, changes in temperature and diffusivity [10], as well as absorption and predation from other cells. If the diffusive process occurs over a long distance (i.e., hormone pathways), the reliability of sequential encoded information can degrade significantly.

[1]University of Warwick, United Kingdom. [2]Johannes Kepler University Linz, Austria. [3]Beijing University of Posts and Telecommunications, China. *Corresponding Author. This research has been funded by Royal Society & NSFC Co-Funded Grant (IE150708) and US Air Force Grant (16IOE064).

In traditional wireless systems, static relays are used to improve signal quality and coverage expansion [11]. Likewise, several researchers have proposed static relays to improve reliability [1], [12]–[14], but this maybe hard to implement in fluidic environments, as it requires premature planning with prior knowledge of stochastic diffusion propagation paths. Inspired by nature, some bacteria can act as mobile relays for carrying DNA encoded messages (i.e., plasmids) and navigate complex in vivo channels and overcoming the aforementioned environmental changes. The navigation process of bacterial relays are known as chemotaxis [15]. This paper will explore the energy efficiency of this mobile relay mechanism as a stimulus for future research further down the development pathway.

A. Review of Bacterial Relay Research

In conventional wireless communication systems, *mechanical relaying* has been widely studied as an energy efficient delay-tolerant protocol [16], [17]. The advantages of using it includes enhancing the cell coverage, spatial reuse of the scarce wireless resources and enhanced throughput [18]. Moreover, it could potentially achieve order of magnitude reductions in the end-to-end communication energy consumption by the network [19] [1]. Similar to mechanical relaying, chemotaxis in biological systems perform similar functions in the context of molecular communications by picking up information macro molecules (i.e., plasmids) and delivering them to a receiver [20], [21]. A key advantage of such systems is that the information molecules can be protected in bacteria from chemical degradation and predation from the environment [22]. For example, *E. coli* bacteria carries information and moves in accordance to a biased random walk in response of a chemical stimulus from the receiver [23]. Continuing this idea, nano-network architecture using flagellated bacteria for transporting DNA encoded information was proposed in [15], and further analyzed in terms of capacity and end-to-end delay [24].

[1]Note the mobility energy of mechanical relays are not considered as the information packets are piggy-backing existing mobility systems.

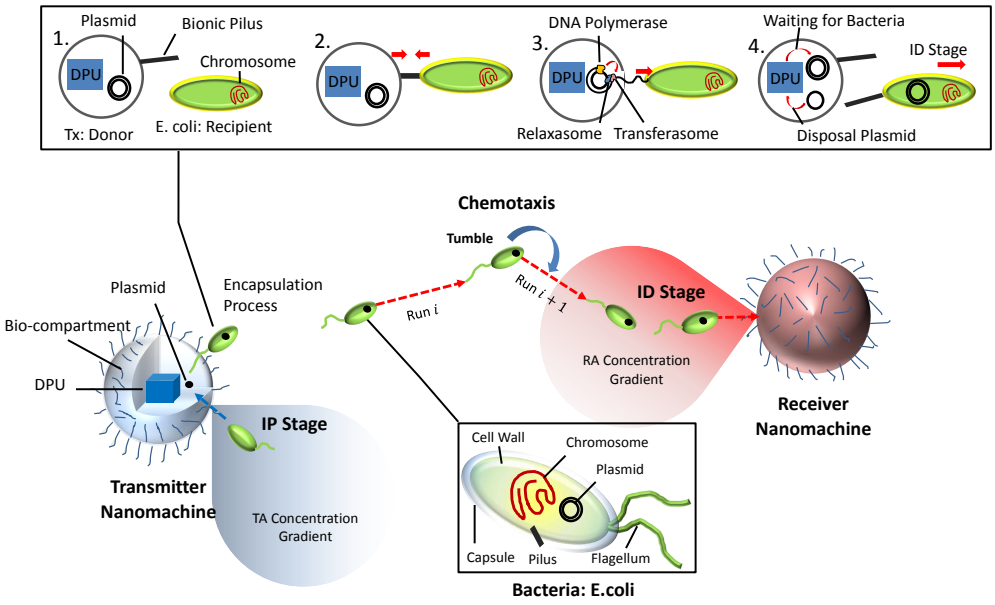

Fig. 1. Communication Steps of Molecular Communication via Bacteria Relaying

More recently, [25] proposed analytic models to estimate the amount of time for a random bacteria chemotaxis pick up and delivery of an information plasmid.

Although the bacteria relaying mechanism has been widely studied in both cell biology and biological physics [24], the energy efficiency analysis of the information transfer process is still lacking. As we know from conventional mechanical relaying, the orders of magnitude improvements in energy efficiency is one of the key benefits of this class of protocols. However, unlike the traditional wireless communication, where devices can be easily connected to external power supply or employ macroscale batteries; the energy supply for nanomachines and biological systems is scarce and limited, and often require scavenging. In fact, this is gaining increasing attention in research, such as a recent paper on joint energy harvesting and data transfer from information molecules [5], [26]. Alternatively, the nanomachines need to be able to covert various energy forms (e.g., electric, chemical energy) into mechanical work [27] and the bacteria need to consume food (e.g., chemical compounds) [28] for the information relay and delivery. In the state-of-art of molecular communication and nanotechnology, targeted drug delivery is one of the applications where energy supply is a fundamental limit to how effectively nano-machines can operate, and many complex fuel systems have been proposed [29], which further highlights the importance of energy consumption in nano-machines.

B. Contribution and Organization

The main contribution of this paper is to establish an information delivery energy model for molecular communication via bacteria relays and analyze the energy efficiency of the process in comparison with conventional MCvD across multiple distances and environmental conditions. In Section II, the paper will first introduce the communication steps and the synthetic biology equivalent model. In Section III, we will present the energy and energy efficiency models for molecular communication via bacteria. Finally in Section IV, we will carry out comparative numerical analysis on the energy efficiency and communication reliability of the chemotaxi system and conventional MCvD system.

II. Molecular Communication via Bacteria

A. Biological Fundamentals

1) Bacteria as Chemotaxis: In terms of physical dimensions, the bacteria relays are normally rod-shaped with 2 μm long and 1 μm wide. We illustrate an example bacteria *Escherichia coli (E.coli)* in Fig. 1. In terms of navigation, *E. coli* is able to sense at least 12 different attractants using its chemoreceptor and it has short-term memory (spanning a few seconds [30]) to remember the attractant concentration gradient. *E. coli* has selective attractant processing, allowing precise

navigation [24]. In terms of propulsion, *E. coli* uses its flagella (a long tail-like appendages) for propelling and rotation in fluidic environments. With the ability of sensing attractants' concentration gradient, the bacteria could swim towards higher concentrations of preferred attractant. This information delivery process is known as *Chemotaxis*.

2) Implementation using Nanomachines: In order to reverse engineer the chemotaxis process, nanomachines are required. Nanomachines are the artificial devices in nano-scale with potential features including computing, sensing and actuation tasks. Today, we are able to manufacture bio-hybrid nanomachines ranging from 5 to 100μm in diameter [4]. Such machines can contain: 1) *DNA Processing Unit* (DPU) to embed artificial information through the synthesis of DNA (forms a plasmid) [31], 2) *Bio-Compartment* to store the produced plasmid, and 3) *Bionic Pilus*[2] to transfer the plasmid to bacteria carrier. In terms of assisting the navigation of the previously mentioned bacterial carrier, the nanomachine can further emit chemical attractant to guide the bacteria [24]. The transmitter distinguishes itself by emitting *transmission attractant* (TA) at a constant rate to creating a concentration gradient in the channel. This serves the purpose of luring empty bacteria carrier to pick up the information. Likewise, the receiver nanomachine transmits *reception attractant* (RA), which serves the purpose of luring information bearing bacteria to the receiver.

B. Communication Mechanism

We illustrate the communication mechanism in Fig. 1. The communication mechanism has 5 steps namely *Encoding, Encapsulation, Propagation, Decapsulation,* and *Decoding*.

1) Encoding: At the beginning of the communication, the DPU starts encoding the message by transferring in a double-stranded DNA molecule. This molecule will then be formed as a plasmid which is a circular DNA strand with capability of self-replication and self-transfer by the DPU. The plasmids are stored in the transmitter *bio-compartment* and at the mean time the transmitter starts releasing the TA in order to attract the empty bacteria carriers in the vicinity.

2) Encapsulation: Encapsulation process is an biological technology which is used to transfer genetic materials from man-made nanomachines to another nanomachines or bio-organism. *Encapsulation* is inspired by *bacterial conjugation* [3] in nature. In Fig. 1, *Encapsulation* happens when the bacterial carrier comes closely enough to the transmitter nanomachine. The transmitter will first act as a donor to attach the bacteria by the *bionic pilus*, which will retract to get the carrier in physical contact with the transmitter. The membranes of both transmitter and bacterium is now connected and a single stranded DNA will be unwounded from the encoded plasmid and then passed to the bacterial carrier. After the single stranded DNA has been transferred, it replicates to a full plasmid in the bacterial carrier while the transmitter and carrier separate. In our case, the remaining part of plasmid in the transmitter is discarded.

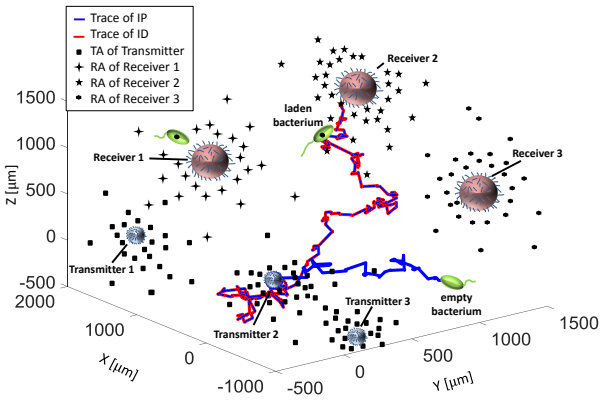

Fig. 2. Plot of the bacteria relay mechanism IP and ID stages with an example trace. The bacterium starts at (1000μm, -500μm, -200μm) and swim to the transmitter Tx 2 (blue round located at (0μm, 0μm, 0μm) with $r_{\mathrm{T}} = 10\mu$m) to pick up the plasmid. Once the plasmid has been picked up, the bacterium swims to the receiver Rx 2(red cross located at (1200μm, 1200μm, 1200μ) with $r_{\mathrm{R}} = 50\mu$m) for delivery.

3) Propagation: The *propagation* of the bacteria in the environment guided by attractants is *chemotaxis*, its movement modeled by a modified version of *Pearson-Rayleigh* random walk [23], [34], which is represented repeating of two stages. In stage a), the bacteria propels over a straight line at constant speed for exponential distributed amount of time. In stage b), the bacterium tumbles around uniformly choosing a new direction arbitrarily between 0 and 2π. The displacement in stage a) is:

$$\Delta r_i = v_i^{\mathrm{prop}} T_i^{\mathrm{prop}}, \tag{1}$$

where Δr_i, v_i^{prop}, and T_i^{prop} denote the displacement, propelling velocity and propelling duration for ith run. T_i^{prop} is exponentially distributed random variable with rate λ_{prop}. Between ith and $i+1$th propelling, the bacteria

[2]A pilus is a hair like appendage found on the surface of many bacteria for direct contact of two bacteria [32].

[3]*Bacterial conjugation* is the transfer of genetic material between bacterial cells by direct cell-to-cell contact or a bridge-like connection between two cells [33].

tumble and choose a new direction. In the tumble stage b), the new angle for the direction of motion is given as,

$$\Theta_{n+1} = \Theta_n + \gamma_n, \tag{2}$$

where Θ_{n+1} and γ_n represent the previous angle of motion and the angular variation due to bacteria tumbling. γ_n is assumed to be uniformly distributed on $(0, 2\pi]$.

We define the propagation process from bacteria's original position to transmitter and from transmitter to receiver after *encaspulation* as the *Information Pick-up* (IP) and the *Information Delivery* (ID) stages respectively. IP and ID stages are two independent random walk processes. Fig. 2 shows a simulation trace of the molecular communication via bacteria IP (blue line) and ID (red line) stages with multiple transmitters and receivers in the aqueous medium.

4) Decapsulation and Decoding: Once the information bearing bacteria arrives at the receiver and connects by the *bionic pilus*, the receiver decapsulates the plasmid and release the empty bacteria back to the environment for the IP stage. In the decoding step, the DPU of the receiver determines the structure of the plasmid by sequencing it and then extract the information from the message region of the plasmid. The receiver finally processes the message and ends the communication.

III. Propagation and Energy Model

In this section, we outline the analytic model for the bacteria movement in the environment and the complete energy model of the process. Firstly we introduce the system parameters and a set of assumptions for the communication model. Secondly we analyze the propagation model of IP and ID stages to derive the end-to-end deliver probability. Finally we establish the energy model including the whole communication steps for the molecular communication via bacteria relaying and present the energy efficiency expression to show how much energy could be efficiently used by utilizing bacteria as information carrier.

A. Propagation Channel Model

We consider a 3-dimension (3-D) aqueous environment represented by a cubic area with $X\mu$m side length. In order to simplify the simulation process, there are several assumptions are applied:

1) The environment is assumed to be free from biased flow currents and free diffusion takes place and the bacteria will bounce back at the boundary;
2) A multiple transmission system is considered, where there are M pairs of transmitters and receivers, and a population of Q bacteria units are used as mobile relays. All the transmitters, receivers and bacteria are assumed to be deployed uniformly in the environment. The size of bacteria is assumed to be significantly smaller than transmitter and receiver;
3) The transmitters have capture radius r_{T}, where inside the radius we assume the bacteria will be successfully connected, and the receivers have reception radius r_{R} where we assume the plasmid is received once the bacteria move in the reception radius;
4) The receivers are assumed to be able to count the number of received plasmid in any given time interval and duplicate messages are able to be deleted by the receiver [4].
5) We assume the communication process happened during the bacterial *lag-phase*, where the the bacteria adapt themselves to growth conditions, and they are maturing themselves and not yet able to divide. Therefore, bacteria death is also not considered.
6) The distance between one of the pairs of transmitter and receiver is denoted as d.

We now consider a single bacterium and we assume the bacterium swims at a constant speed v and can change direction instantaneously [25]. We define the time it takes the bacterium arrive at the the destination (Tx in IP stage and Rx in ID stage respectively) as their respective *First Passage Times* (FPT). While M is large, it is reasonable to assume that despite the purposeful movement of bacteria, they are nonetheless i.i.d., and the overall distribution of bacteria is therefore random and uniform throughout the aqueous medium. Thus, consider the bacteria's location in steady-state, which is expressed as $f(x, y, z)$, and the spatial position of the bacteria is uniform over X^3 in 3D environment, given as,

$$f(X) = \frac{1}{X^3}. \tag{3}$$

Since the size of the bacteria is assumed to be significantly smaller than transmitter and receiver, for the IP stage, the FPT can be approximated by the probability to 'cover' a point (bacteria) uniformly distributed in the X^3 by the transmitter, which is an exponential distribution with a rate given by [25]:

$$\lambda_{\mathrm{P}} \approx \frac{2\pi r_{\mathrm{T}}^2 Q v}{X^3}. \tag{4}$$

[4]This can be accomplished if the messages are encoded as DNA/RNA barcodes for example, which can achieve sufficiently low error rate [35]

Similarly, the FPT rate λ_{D} of ID stage is given as:

$$\lambda_{\mathrm{D}} \approx \frac{2\pi r_{\mathrm{R}}^2 v}{Y^3}, \tag{5}$$

where Y is the side length of the cubic area from the transmitter to the receiver with diagonal of d, therefore, $\lambda_{\mathrm{D}} \approx \frac{2\pi r_{\mathrm{R}}^2 v}{\sqrt{\frac{d^2}{3}}^3} = \frac{6\sqrt{3}\pi r_{\mathrm{R}}^2 v}{d^3}$.

Since the IP and ID stages can be treated are independent processes, the overall FPT for a plasmid been successfully picked up and delivered is the summation of both the FPT of IP and the FPT of ID. As they are both independent exponentially distributed random variables, the overall FPT $f_{\mathrm{T}}(t)$ is the convolution of the aforementioned FPTs:

$$\begin{aligned} f_{\mathrm{T}}(t) &= \int_0^{\infty} f_{\mathrm{P}}(x) f_{\mathrm{D}}(t-x)\mathrm{d}x \\ &= \frac{\lambda_{\mathrm{P}}\lambda_{\mathrm{D}}}{\lambda_{\mathrm{P}} - \lambda_{\mathrm{D}}} \left(e^{-\lambda_{\mathrm{D}} t} - e^{-\lambda_{\mathrm{P}} t}\right), \end{aligned} \tag{6}$$

where $f_{\mathrm{P}}(x)$ and $f_{\mathrm{D}}(x)$ are the exponential distribution with rate in Eq. 4 and Eq. 5 respectively.

We assume each transmitter produce one plasmid. Therefore, the number I of plasmid being picked up by bacteria during a finite time period T is given as,

$$\begin{aligned} I &= \int_0^{T} M f_{\mathrm{P}}(t)\mathrm{d}t \\ &= M\left[1 - \exp(-\lambda_{\mathrm{P}} T)\right] \end{aligned} \tag{7}$$

The number N of plasmid been successfully picked and delivered in T is given as,

$$\begin{aligned} N &= \int_0^{T} M f_{\mathrm{T}}(t)\mathrm{d}t \\ &= M\frac{\lambda_{\mathrm{P}}\left(-e^{-\lambda_{\mathrm{D}} T}\right) + \lambda_{\mathrm{D}}\left(e^{-\lambda_{\mathrm{P}} T} - 1\right) + \lambda_{\mathrm{P}}}{\lambda_{\mathrm{P}} - \lambda_{\mathrm{D}}}. \end{aligned} \tag{8}$$

B. Attractant Gradient

The process of *chemotaxis* requires the existence of attractant gradient. We model both the transmission attractant (TA) and reception attractant (RA) of different receivers as a continuously released process with the same diffusion coefficient D_{A} at the same rate of N_{A} [mol/s]. Thus, the process of the releasing attractants can be considered as a step function. According to Fick's second law of diffusion, the impulse response of a diffusion channel $\phi(x, y, z, t)$ at a location of (x, y, z) from the source in 3D medium is given as [36],

$$\phi(x, y, z) = \frac{2\exp\left[-\frac{(x^2+y^2+z^2)}{4D_{\mathrm{A}}t}\right]}{(4\pi D_{\mathrm{A}} t)^{3/2}} = \frac{2\exp\left[-\frac{L^2}{4D_{\mathrm{A}}t}\right]}{(4\pi D_{\mathrm{A}} t)^{3/2}}, \tag{9}$$

where L is the distance away from the attractant origin. Thus, the step response $S(L, t)$, which represents the concentration of the attractants at distance L over time t is given as [36],

$$S(L, t) = \frac{N_{\mathrm{A}}}{2\pi D_{\mathrm{A}} L}\mathrm{erfc}\left(\frac{L}{2\sqrt{D_{\mathrm{A}} t}}\right). \tag{10}$$

Therefore, the concentration gradient at distance L can be found via the derivative of distance, given as,

$$\begin{aligned} &\frac{\partial}{\partial L}\left(\frac{N_{\mathrm{A}}}{2\pi D_{\mathrm{A}} L}\mathrm{erfc}\left(\frac{L}{2\sqrt{D_{\mathrm{A}} t}}\right)\right) \\ &= \frac{N_{\mathrm{A}}\left(-\sqrt{\pi}\mathrm{erfc}\left(\frac{L}{2\sqrt{D_{\mathrm{A}} t}}\right) - \frac{L e^{-\frac{L^2}{4D_{\mathrm{A}} t}}}{\sqrt{D_{\mathrm{A}} t}}\right)}{2\pi^{3/2} D_{\mathrm{A}} L^2}. \end{aligned} \tag{11}$$

C. Energy Efficiency

In the molecular communication via bacteria system, the energy is spent for the production of messenger molecules (*plasmid*), their release to the bacteria, propagation to the target and extraction cost for the receiver. Previously, we introduced the 5 energy consuming communication steps: *Encoding, Encapsulation, Propagation, Decapsulation* and *Decoding*.

Encoding: In order for the DPU to produce such plasmid, every single plasmid has a fixed energy cost of 202.88 zJ [5] [33]. We define the energy cost of encoding and synthesizing of a single *plasmid* as $E_{\mathrm{P}} = 202.88$ zJ, and producing M plasmids need $M \times E_{\mathrm{P}}$ zJ.

Encapsulation: The energy cost of passing a plasmid to the single bacterium carrier is 2 units of ATP [6], which in turn equals 2×83 zJ [32], [37]. We define the energy cost of passing one *plasmid* to one bacterium via the is $E_{\mathrm{B}} = 166$ zJ, and I number of plasmids are picked up according to Eq. 7, which requires $I \times E_{\mathrm{B}}$ zJ energy.

Propagation: We consider the energy cost for the bacterial motility as EC_{M}, which is defined as the sum of energy cost of propulsion EC_{s} and tumbling EC_{t}. [38] proposed the expression of EC_{M}, given as,

$$EC_{\mathrm{M}} = EC_{\mathrm{s}} + EC_{\mathrm{t}} \approx \frac{kT_a D_m}{{r_b}^2} + 3{r_b}^3, \tag{12}$$

where k is the Boltzmann's constant, T_a is absolute temperature, D_m is translation molecular diffusion coefficient of bacteria and r_b is the radius of the bacteria. The constant 3 is in the centimeter-gram-second unit system.

[5]The zeptojoule (zJ) is equal to one sextillionth (10^{-21}) of one joule.

[6]Adenosine triphosphate (ATP) is a small molecule used in cells as an coenzyme for energy transfer.

[t]
TABLE I
SYMBOLS AND COMMON VALUES

Parameter	Definition	Values
X	Side of cubic area	$10^4 \mu$m
r_{T}	Tx radius	10μm [40]
r_{R}	Rx radius	50μm [24], [25]
d	Distance between Tx and Rx	up to $10^4 \mu$m
Q	No. of bacteria	up to 500 [42]
r_b	Bacterial radius	1μm [38]
v	Bacteria speed	20μm/s [42]
D_{m}	Bacterial translation diffusivity	$5.19 \times 10^{-10}\text{m}^2$/s [38]
M	No. of Tx-Rx pair	up to 1000
N_{A}	Attractant releasing rate	10^{-11} mol/s [24]
D_{A}	Attractant diffusion coeffcient	10^{-9}m^2/s [24]

By assuming the radius r_b of E.coli. in our model is 1 μm and $D_m = 5.19 \times 10^{-6}\text{cm}^2/\text{s}$ at 25°C [39]. Therefore, EC_{M} is calculated to be $EC_{\text{M}} \approx 2165.4$ [zJ/s] and the total energy cost for the bacterial motility during time T is $EC_{\text{M}} \times T$ [zJ].

Decapsulation and Decoding: reverse of the *encapsulation* process and as such the energy cost is defined as $E_{\text{D}} = E_{\text{B}}$. Finally, after the Rx collect the plasmid, the DPU needs to extract the information from the plasmid and decode the information. The extraction and decoding cost from plasmid is defined as E_{E} which consumes roughly 10 ATP of energy [37], [40] which gives $E_{\text{E}} = 830$zJ. Thus, the energy cost of decapsulation and decoding is based on the number of delivered plasmids N in Eq. 8 given as $N \times (E_{\text{D}} + E_{\text{E}})$.

Total Energy: Therefore, the total energy cost E_{Total} for the communication process is given as,

$$E_{\text{Total}} = M \times E_{\text{P}} + I \times E_{\text{B}} + Q \times EC_{\text{M}} \times T + N \times (E_{\text{D}} + E_{\text{E}}). \quad (13)$$

Each plasmid is regraded as an information packet containing 60 bits [41], thus the energy efficiency ρ is defined as the total energy usage per delivered information bits, given as,

$$\rho = \frac{E_{\text{Total}}}{60 \times N} \quad (14)$$

IV. NUMERICAL ANALYSIS

In this section, we numerically analyze the performance of the energy efficiency of the molecular communication via bacteria (MCvB) and compare it with conventional molecular communication via diffusion (MCvD). The energy model for MCvD can be found in the Appendix. Table I shows the symbols used in the model and their values from references, which considered the same aqueous environment in the numerical analysis.

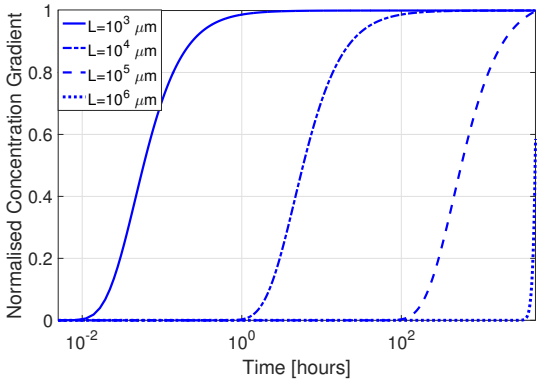

Fig. 3. Normalized concentration gradient as a function of time, where $D_{\text{A}} = 1000\mu\text{m}^2/\text{s}$, and $N_{\text{A}} = 10^{-11}$mol/s.

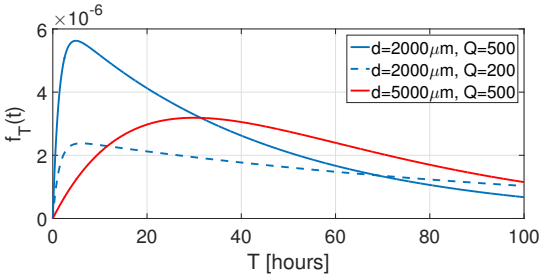

Fig. 4. The probability density function of successfully deliver a plasmid to the receiver where $X = 10^4 \mu m$

A. Determination of Communication Range Based on the Attractant Gradient

We first discuss the communication range for the molecular communication via bacteria. According to Eq. 11, we show the normalized attractant gradient as a function of time in Fig. 3. It can be observed that the bacteria need to wait 0.01, 1, 100 and approximately 3000 hours for the existence of attractant gradient at a distance of 10^3, 10^4, 10^5, and 10^6 μm respectively. We consider the bacterial communication happened during the bacterial *lag-phase*, which can be maintained up to 48 hours [43], [44] without considering bacterial division and death. Thus, the maximum range of the communication model is in the order of 10^4 μm and the total time is considered up to 10 hours for the rest of the simulation.

B. First Passage Probability

We then analyze the first passage probability $f_T(t)$ in Fig. 4. As we can see: for a fixed distance between transmitter and receiver, the higher number Q of deployed bacteria, the higher peak value of $f_T(t)$. On

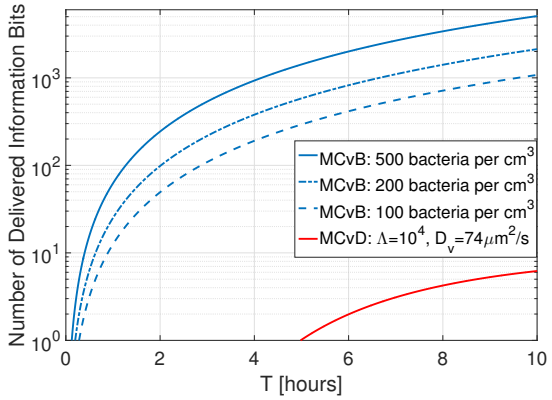

Fig. 5. The plot of the number of information bits been successfully delivered as function of time period T where $d = 2000\mu m, M = 1000, X = 10^4 \mu m$.

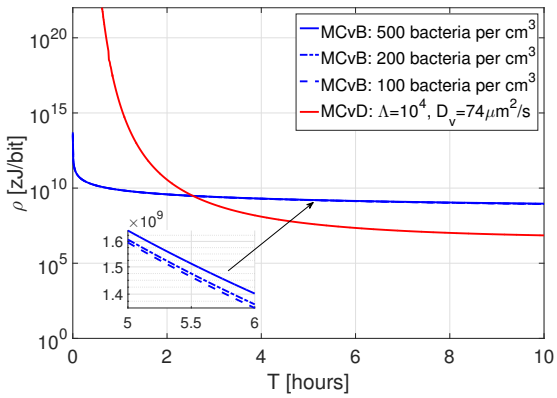

Fig. 6. The comparison of the energy efficiency between molecular communication via bacteria and diffusion over time period T where d is fixed at $d = 5000\mu$m, $X = 10^4 \mu m$

the other hand, if the Q is fixed, when the distance d increases, the peak value of $f_T(t)$ will decrease and the time to reach the peak value will shift to right which makes the peak $f_T(t)$ point longer to reach. In summary, increasing the number of bacteria and decreasing the communication distance greatly affect the probability of successful delivery.

We now consider the number of information bits being successfully delivered within a specific time period T and compare the performance with molecular communication via diffusion. In Fig. 5, the blue lines compare the difference between 500, 200, and 100 bacteria relays deployed in the environment. With fixed side length X, changing the number of bacteria varies the density of the bacteria in the environment ($\frac{Q}{X^3}$ in Eq. 4). We can observe that with a the higher bacterial density, the higher number of information bits can be delivered in the same time period (e.g. at a fixed T). Moreover, higher bacterial density can also advance the time for the first information bit delivered. Compared with the MCvD in Eq. 16 (see Appendix), we can see the MCvD needs significantly longer time to deliver the first bit and the total number of information bits delivered is also orders of magnitude less.

C. Energy Efficiency

1) Effect of Time: We now discuss the energy efficiency (EE) as a function of time for both MCvB and MCvD. In Fig. 6, we can see the EE of MCvB dramatically decreases at the beginning and then continuously decrease slightly after 1 hour. While changing the number of bacteria deployed in the environment, the EE has little difference. With comparison to the MCvD (red line), the energy efficiency is orders of magnitudes higher than MCvB before $T \approx 2.5$ hours, after then, the EE of MCvD continuously decreases below EE of MCvB. As EE is defined as [zJ/s], which means the energy consumption for each information bit successfully delivered, we hope the EE is the smaller the better. Thus, based on Fig. 6, it can be summarized that MCvB is suitable for *delay-sensitive* molecular communication.

2) Effect of Distance: In Fig. 7, the EE is compared over distance. We can observe that, the EE of both MCvB and MCvD will increase over distance. But the increasing rate of MCvD is higher than the rate of MCvB, which indicates that EE of MCvD is more sensitive than EE of MCvB on distance. Again, the lower of the bacterial density will reduce the EE, but the overall difference is little. Furthermore, in Fig. 7(a), the EE of MCvB is lower than MCvD after $d \approx 3200\mu$m at T=1 hour. Afterwards, the EE of MCvB will be always higher than MCvD. In Fig. 7 (b), (c), it can be observed that the difference between EE of MCvB (blue lines) and MCvD (red line) is decreasing over distance. Therefore, it can be concludes that MCvB is further suitable for *long-distance* molecular communication.

3) Effect of Bacterial Density: Finally, we show the effect of bacterial density in Fig. 8. The results are straight forward that the bacterial density has little effects on the EE, where the black lines tends to be flat, which conforms the findings in Fig. 6 and Fig. 7 on bacterial density. With the conclusion of the bacterial density on EE, we concludes that increasing the bacterial density is able to increase the probability of successfully delivering plasmid and the total number of information bits. However, the higher bacterial density does not result a better EE. This fact is of

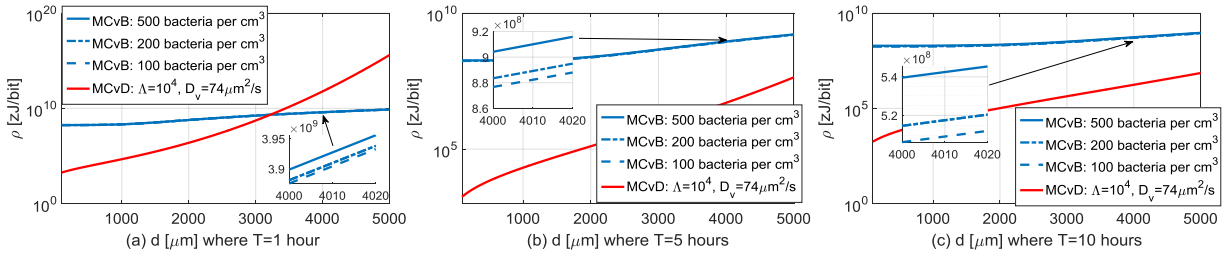

Fig. 7. The comparison of the energy efficiency between molecular communication via bacteria and diffusion over distance d where $D = 74\mu\text{m}^2/\text{s}$, $\Lambda_{1/2} = 10^4\text{s}$, $M = 1000$, $X = 10^4\mu m$.

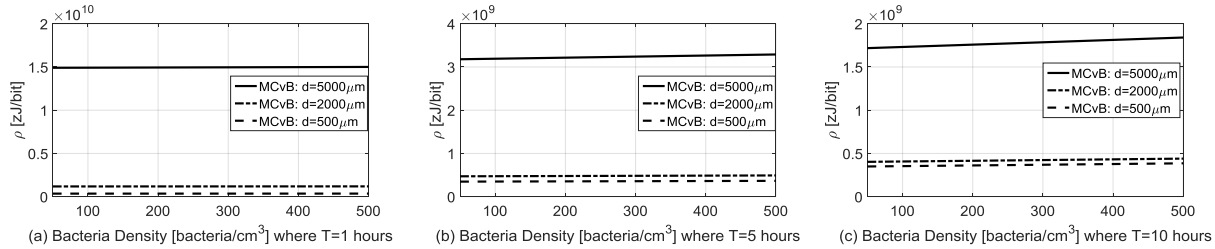

Fig. 8. The plot of energy efficiency as a function of bacterial density $\frac{Q}{X^3}$ where d is fixed at $2000\mu m$.

special importance in practical applications, where the population of bacteria deployed cannot be infinitely increased for better EE and without harmful effects on bio-organisms.

V. Conclusions

In this paper we introduced the communication model of molecular communication via bacteria (MCvB) and proposed an energy efficiency model for cross-comparison between different communication systems. In particular, we compared the energy efficient performance for both MCvB and molecular communications via diffusion (MCvD). We show that MCvB has better first passage time profile and the total number of information bits being delivered than MCvD. The energy efficiency of MCvB is superior for long distance or delay-sensitive communications (i.e., bacteria swimmers are more efficient than free diffusion), but inferior over short distances and delay-tolerant communications.

Appendix

The energy efficiency of molecular communication via bacteria is compared with molecular communication via diffusion (MCvD). The communication system of MCvD is considered as the same except the transmitter of the MCvD is a point source of a size equal to zero. The information molecules are assembled into vesicle [40] (instead of bacteria) and the vesicle diffuse to the receiver. In MCvD, the first passage probability $\phi(t)$ to a spherical absorber is given as [45], [46],

$$\phi(t) = \frac{r_{\text{R}}}{d}\frac{d - r_{\text{R}}}{\sqrt{4\pi D_{\text{v}} t^3}}\exp\left[-\frac{(d - r_{\text{R}})^2}{4D_{\text{v}} t}\right], \qquad (15)$$

where D_{v} is the diffusion coefficient of the vesicle in the specific environment with value of $7.4 \times 10^{-11}\text{m}^2/\text{s}$ [40]. We further consider the vesicles suffer from the molecular degradation [47], [48] which is modelled as an exponential distribution $\exp(-\lambda t)$, where: $\lambda = \frac{\ln(2)}{\Lambda_{1/2}}$ and λ is the rate of degradation and $\Lambda_{1/2}$ is the corresponding half-life of the vesicle molecule. Therefore, the number R of information molecules can be received of MCvD

is given as,

$$
\begin{aligned}
R &= \int_0^T M\phi(t)\exp(-\lambda t)\mathrm{d}t \\
&= \frac{Mr_{\mathrm{R}}}{d}\exp\left[-\sqrt{\frac{\lambda}{D}}\left(d-r_{\mathrm{R}}\right)\right] \\
&- \frac{Mr_{\mathrm{R}}}{2d}\exp\left[-\sqrt{\frac{\lambda}{D}}\left(d-r_{\mathrm{R}}\right)\right] \\
&\times \left\{\mathrm{erf}\left(\frac{d-r_{\mathrm{R}}}{\sqrt{4DT}}-\sqrt{\lambda T}\right)+\exp\left(2\sqrt{\frac{\lambda}{D}}\left(d-r_{\mathrm{R}}\right)\right)\right. \\
&\times \left.\left[\mathrm{erf}\left(\frac{d-r_{\mathrm{R}}}{\sqrt{4DT}}+\sqrt{\lambda T}\right)-1\right]+1\right\},
\end{aligned}
\tag{16}
$$

where

The energy cost of MCvD is similar to the molecular communication via bacteria, but the mobility energy cost for vesicles is 0 as the vesicle is freely diffusing in the environment which will not cost any energy for the propagation. We assume the vesicle contains the same length of bits information for the purpose of comparison. Thus, the energy efficiency expression of MCvD is given as,

$$
\begin{aligned}
\rho &= \frac{E_{\mathrm{Total}}}{60\times R} \\
&= \frac{M\times\left(E_{\mathrm{P}}+E_{\mathrm{B}}\right)+R\times\left(E_{\mathrm{D}}+E_{\mathrm{E}}\right)}{60\times R}.
\end{aligned}
\tag{17}
$$

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